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FOR

HIGH PRECISION CHARGE PUMP REGULATION

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HIGH PRECISION CHARGE PUMP REGULATION

FIELD OF THE INVENTION

[0001] The present invention relates generally to the field of computers and computer systems. More particularly, the present invention relates to a method and apparatus for high precision charge pump regulation.

BACKGROUND OF THE INVENTION

[0002] Many of today's computing applications such as cellular phones, digital cameras, and personal computers, use nonvolatile memories to store data or code. Nonvolatility is advantageous because it allows the computing system to retain its data and code even when power is removed from the computing system. Thus if the system is turned off or if there is a power failure, there is no loss of code or data.

[0003] One example of a nonvolatile memory device is the flash Electrically Erasable Programmable Read-only Memory (flash EEPROM or flash memory). Flash memory can be programmed by the user, and once programmed, the flash memory retains its data until the memory is erased. Electrical erasure of the flash memory erases the contents of the memory of the device in one relatively rapid operation. The flash memory may then be programmed with new code or data.

[0004] Flash memories have been used in portable computers and similar circuitry as both read only memory and as long term storage which may be both read and written. However, the tendency has been to reduce the power requirements of such portable computers to make systems lighter and to increase the length of use between recharging. This has required that the voltage potentials available to program the flash memory arrays

be reduced. Flash memories must be able to operate in systems where a VCC supply voltage of 5V, 3V, or an even smaller voltage is available to circuit components.

[0005] However, performing program and erase operations in flash memory components requires that greater voltage than that supplied to the component be applied to the flash memory cells. For example, a program operation may require that approximately 10.5V be applied to a memory cell. In order to achieve this voltage, a charge pump circuit is required in the flash memory component. A positive charge pump can take a supplied VCC voltage and create a voltage sufficient for program operations. The charge pump must also be able to deliver sufficient current at the required voltage levels.

[0006] Furthermore, as the electronic applications and devices that use integrated circuit components move to lower and lower power, the flash memory components in these applications also have to be more power efficient. One possible area for optimization is the charge pump circuitry.

BRIEF DESCRIPTION OF THE DRAWINGS

[0007] The present invention is illustrated by way of example and not limitations in the figures of the accompanying drawings, in which like references indicate similar elements, and in which:

[0008] **Figure 1** illustrates one embodiment of a cellular telephone using a flash memory device;

[0009] **Figure 2** is a block diagram of one embodiment of a computer system including a component utilizing a high precision charge pump regulation in accordance with the present invention;

[0010] **Figure 3** is a block diagram of a flash memory circuit using a high precision charge pump regulation mechanism of one embodiment;

[0011] **Figure 4** is a block diagram of one embodiment of a charge pump including a high precision charge pump regulation mechanism in accordance with the present invention; and

[0012] **Figures 5A-D** are flow diagrams illustrating one embodiment of a method for high precision regulation of a charge pump.

DETAILED DESCRIPTION

[0013] A method and apparatus for a high precision charge pump regulation is disclosed. The embodiments described herein are described in the context of a memory, but are not so limited. Although the following embodiments are described with reference to a flash memory, other embodiments are applicable to other types of integrated circuits or logic devices. The same techniques and teachings of the present invention can easily be applied to other types of circuits or semiconductor devices that use charge pumps.

[0014] In the following description, for purposes of explanation, numerous specific details are set forth in order to provide a thorough understanding of the present invention. One of ordinary skill in the art, however, will appreciate that these specific details are not necessary in order to practice the present invention. In other instances, well known electrical structures and circuits have not been set forth in particular detail in order to not necessarily obscure the present invention.

[0015] A flash EEPROM memory device (cell) is a floating gate MOS field effect transistor having a drain region, a source region, a floating gate, and a control gate. Conductors are connected to each drain, source, and control gate for applying signals to the transistor. A flash EEPROM cell is capable of functioning in the manner of a normal EPROM cell and will retain a programmed value when power is removed from the circuitry. A flash EEPROM cell may typically be used to store a one or zero condition. If multilevel cell (MLC) technology is used, multiple bits of data may be stored in each flash EEPROM cell. Unlike a typical EPROM cell, a flash EEPROM cell is electrically erasable in place and does not need to be removed and diffused with ultraviolet to accomplish erasure of the memory cells.

[0016] As supply voltages and device sizes continue to decrease, the sensitivity of flash cell devices to variations in temperature, manufacturing processes, and supply voltages does not. Furthermore, as more flash memory devices make use of MLC technology, the circuitry requires more stringent supply voltages and sensing capabilities. This is because MLC flash cells are more susceptible to data errors due to tighter threshold voltage (V_t) ranges in the storage of data bits. For example, a single bit flash cell can use an entire voltage range such as from 2.0 volts up to 4.0 volts to store the value of a single bit of data. For simplicity, the cutoff threshold for determining whether the flash cell is storing a '1' or a '0' bit is 3.0 volts. Thus if the V_t value of a flash cell is greater than 3.0 volts, a '1' is stored therein and if the V_t value is less than 3.0 volts, a '0' is stored therein. But with a MLC flash cell, two bits of data are stored within the same voltage range of 2.0 volts to 4.0 volts. So the two bits in the single MLC flash cell are storing "1, 1" if the V_t value is greater than 3.5 volts, "1, 0" if the V_t value is between 3.0 volts and 3.5 volts, "0, 1" if the V_t value is between 2.5 volts and 3.0 volts, and "0, 0" if the V_t value is less than 2.5 volts. The voltage values of this example have been randomly picked for ease in discussion, but actually voltage values can be much more precise and the range much smaller.

[0017] Existing power circuits do not provide accurate enough voltage levels and can easily vary ± 450 millivolts (mV) from the target value. Whereas a single bit flash variation of between ± 350 mV to 550 mV may be tolerable in a single bit flash environment, a MLC flash environment may require variations to be less than ± 50 mV. A single bit flash cell may still correctly sample, read, verify, and operate with large voltage variations where a MLC flash cell may not. Circuits pertaining to read operations

are extremely sensitive. Read windows and regulation can be the most sensitive circuits of MLC parts because of the voltage tolerances. Thus tighter control of the voltages for programming, erasing, sensing, etc. is necessary in order to store and read the correct data values.

[0018] MLC flash memory generally needs high precision wordline voltages. The segmentation of the threshold voltage ranges for data storage in a MLC flash cell makes the devices more sensitive to voltage levels. Precise voltage levels are needed in order to achieve tight, precise V_t distributions on the flash cells. General charge pump regulation, as well as a second layer of voltage regulation, is also needed to achieve a lower supply voltage variation from the pump supply. However, the present read regulation schemes are extremely costly both in terms of power and die size area. Furthermore, read regulators increase the complexity of the architecture and design of the chip.

[0019] Embodiments of the present invention can provide more accurate supply voltages from charge pumps. For instance, one embodiment of the present invention uses a new single pump regulation circuit to achieve high precision voltage control of approximately ± 50 mV within the target value across a variety of VCC supply voltages, temperatures, and manufacturing process corners.

[0020] Referring now to **Figure 1**, there is an example of a cellular telephone **100** using a flash memory device **110**. The cellular telephone **100** shown in **Figure 1** is a digital phone capable of internet access. For example, a user can download and receive information from the Internet via cellular access. This cellular phone **100** can be a Personal Communications Service (PCS) phone using digital cellular technology such as Code-Division Multiple Access (CDMA), Time Division Multiple Access (TDMA), or

Global System for Mobile (GSM) Communications. Similarly, flash memory can also be used in analog type cellular phones. Thus, the present invention is not limited to any specific combination of hardware circuitry and software.

[0021] Flash memory **110** and a processor **130** are located within cellular phone **100**. Flash memory **110** has been designed to include a fast program mode. Processor **130** can be an embedded processor or a digital signal processing (DSP) chip. The phone **100** of **Figure 1** also includes a access port **120**. Access port **120** can be used to physically link the phone **100** to an external system for code and/or data update. For instance, the flash memory can be updated through the access port interface or through a download via cellular transmission.

[0022] A memory update via the access port **120** is an example of an in-system write. In-system write utilizes the system processor **130** to execute flash memory erase and program algorithms. An engineer creates erase, program and verify algorithms and then downloads these algorithms into the system random access memory (RAM). The processor **130** executes the algorithms and ports code to the flash memory **110** for updates. In-system write is also a way to perform PC BIOS code updates.

[0023] The present invention is not limited to cellular phones. Alternative embodiments of the present invention can be used in other types of devices such as handheld devices and embedded applications. Some examples of handheld devices include Internet Protocol devices, digital cameras, personal digital assistants (PDAs), and handheld PCs. Embedded applications can include a microcontroller, a digital signal processor (DSP), system on a chip, network computers (NetPC), set-top boxes, network hubs, wide area network (WAN) switches, or any other system which uses flash memory

for other embodiments. Flash memory is also used in personal computers (PC) and other computer systems.

[0024] For another embodiment of a system, a charge pump can be used with a system on a chip. One embodiment of a system on a chip comprises of a processor and a memory. The memory for one system is a flash memory. The flash memory can be located on the same die as the processor and other system components. Additionally, other logic blocks such as a memory controller or graphics controller can also be located on a system on a chip. By including one embodiment of the present invention on the system on a chip, the flash memory can be updated quickly and with minimal inconvenience to a user.

[0025] Referring now to **Figure 2**, an exemplary computer system **200** is shown. System **200** includes a component, such as a flash memory, to employ a high precision charge pump regulation in accordance with the present invention, such as in the embodiment described herein. System **200** is representative of processing systems based on the PENTIUM® III, PENTIUM® 4, Itanium™, and/or StrongARM™ microprocessors available from Intel Corporation of Santa Clara, California, although other systems (including PCs having other microprocessors, engineering workstations, set-top boxes and the like) may also be used. In one embodiment, sample system **200** may execute a version of the WINDOWS™ operating system available from Microsoft Corporation of Redmond, Washington, although other operating systems (UNIX and Linux for example), embedded software, and/or graphical user interfaces, may also be used. Thus, the present invention is not limited to any specific combination of hardware circuitry and software.

[0026] The present enhancement is not limited to computer systems. Alternative embodiments of the present invention can be used in other devices such as handheld devices and embedded applications. Some examples of handheld devices include cellular phones, Internet Protocol devices, digital cameras, personal digital assistants (PDAs), and handheld PCs. Embedded applications can include network computers (NetPC), set-top boxes, network hubs, wide area network (WAN) switches, or any other system that utilizes wireless communications.

[0027] **Figure 2** is a block diagram of one embodiment of a computer system **200** including a component utilizing a high precision charge pump regulation in accordance with the present invention. The processor **202** includes an internal cache memory **204**. The present embodiment is described in the context of a single processor desktop or server system, but alternative embodiments can be included in a multiprocessor system. System **200** is an example of a hub architecture. The computer system **200** includes a processor **202** to process data signals. The processor **202** can be a complex instruction set computer (CISC) microprocessor, a reduced instruction set computing (RISC) microprocessor, a very long instruction word (VLIW) microprocessor, a processor implementing a combination of instruction sets, or any other processor device, such as a digital signal processor, for example. The processor **202** is coupled to a processor bus **210** that transmits data signals between the processor **202** and other components in the system **200**. The elements of system **200** perform their conventional functions that are well known to those familiar with the art.

[0028] System **200** includes a memory **220**. Memory **220** can be a dynamic random access memory (DRAM) device, a static random access memory (SRAM) device, flash

memory device, or other memory device. Memory **220** can store instructions and/or data represented by data signals that can be executed by the processors **202**. An internal cache memory **204** can reside inside the processor **202** to store recently used data signals from memory **220**. Alternatively, in another embodiment, the cache memory can reside external to the processor **202**.

[0029] A system logic chip **216** is coupled to the processor bus **210** and memory **220**. The system logic chip **216** in the illustrated embodiment is a memory controller hub (MCH). The processor **202** communicates to the MCH **216** via a processor bus **210**. The MCH **216** provides a high bandwidth memory path **218** to memory **220** for instruction and data storage and for storage of graphics commands, data and textures. The MCH **216** is to direct data signals between the processor **202**, memory **220**, and other components in the system **200** and to bridge the data signals between processor bus **210**, memory **220**, and system I/O **222**. In some embodiments, the system logic chip **216** can provide a graphics port for coupling to a graphics controller **212**. The MCH **216** is coupled to memory **220** through a memory interface **218**. The graphics card **212** is coupled to the MCH **216** through an Accelerated Graphics Port (AGP) interconnect **214**.

[0030] System **200** uses a proprietary hub interface bus **222** to couple the MCH **216** to the I/O controller hub (ICH) **230**. The ICH **230** provides direct connections to some I/O devices via a local I/O bus. The local I/O bus is a high-speed I/O bus for connecting peripherals to the memory **220**, chipset, and processor **202**. Some examples are the audio controller, firmware hub (flash BIOS) **228**, data storage **224**, legacy I/O controller containing user input and keyboard interfaces, a serial expansion port such as Universal Serial Bus (USB), and a network controller **234**. The data storage device **224** can

comprise a hard disk drive, a floppy disk drive, a CD-ROM device, a flash memory device, and/or other mass storage device.

[0031] For the embodiment of a computing system **200** in **Figure 2**, a wireless transceiver **226** is also coupled to the ICH **230**. The wireless transceiver is capable of receiving and transmitting data from the system **200** through the ICH **230** as well as using wireless signals to receive and transmit data from remote systems. Control of the transceiver **226** resides with device driver software and memory **220**, which communicates with firmware software and memory residing on the wireless transceiver **226**. The processor **202** can execute instructions from memory **220** that cause the processor to send data to and request from the wireless transceiver. Application software and the operating system, working through the wireless transceiver device driver, can interface the wireless transceiver **226**. The wireless transceiver enables the system **200** to communicate with other computers and devices that have wireless capability.

[0032] **Figure 3** is a block diagram of a flash memory circuit **300** using a high precision charge pump regulation mechanism of one embodiment. Reference generator **330** provides a reference voltage **332** to the positive pump **326**. For one embodiment, the positive charge pump **326** and negative charge pump **316** include a self initialization mechanism. The positive pump **326** provides a regulated voltage of approximately five volts over decoder supply line **328** to the decoders **340** of the memory array **350**. The negative pump **316** provides a voltage of approximately negative five volts over decoder supply line **318** to the decoders **340** of memory array **350**. A first oscillator **310** provides a clock signal **312** to a first phase clock generator (or clock driver) **314** that periodically pulses or enables the negative pump **316** during standby mode. A second oscillator **320**

provides clock signals 321, 322 to the reference generator 330 and a second phase clock generator 324. The clock signals 322, 321, periodically pulse or enable the positive pump 326 and the reference generator 330, respectively, when they are in a standby mode. The clock signals 312, 321, 322 may each have a different frequency. The phase clock generators 314, 324, drive the pumping action in the negative charge pump 316 and the positive charge pump 326, respectively. Although the pump outputs 318, 328, of this example are shown as primarily driving the decoders 340 and the memory array 350, the pump outputs also supplies other circuitry on the integrated circuit that need supply voltages other than VCC and ground.

[0033] In this flash circuit 300, the pump regulation mechanism includes a control signal 301 that can enable or disable the second oscillator 320 and the second phase clock generator 324 based on input from the positive pump output feedback loop. Before the output node of the positive charge pump 326 is a large filtering diode device that is part of the pump regulation. This large diode couples the pumped supply voltage from the positive charge pump 326 to the memory array 350 via decoders 340. The diode is also coupled to a feedback loop via a resistor divider. This feedback loop operates to help regulated the charge pump operation. Unlike regulation schemes that use read regulator circuits, embodiments of the present invention do not wastefully pump the output voltage level up to unnecessary levels in order to drop the voltage level back down to a desired value with regulation. Pumping a voltage to a voltage level that is not actually needed by circuits at the pump output can increase power consumption and cause heat dissipation issues. Schemes with read regulators can also consume large amounts of die size as the charge pump has to be large to supply enough current. The embodiments of the pump

regulation of the present invention take a limited amount of die area as the additional circuitry is minimal.

[0034] **Figure 4** is a block diagram of a one embodiment of a high precision charge pump **400** including a pump regulation mechanism in accordance with the present invention. This example embodiment describes a pump based regulation design that includes features such as four phase frequency blocking, low pass diode filtering, and a dual port high gain differential amplifier. The pump **400** of this embodiment can provide an output voltage level that is independent of external current loading. A comparator **410** receives a reference voltage **402** and a pump feedback voltage **462**. The comparator **410** of this embodiment is a dual port high gain differential amplifier that can provide a digital output and an analog output. The reference voltage **402** indicates a voltage at which the charge pump cells **440** should be presently outputting. The comparator **410** takes the reference voltage **402** and examines whether the voltage from the pump feedback loop to determine whether the charge pump **400** is operating as desired.

[0035] The comparator **410** provides two output signals: a bias signal **412** and a frequency block signal **414**. The bias signal **412** is an analog type signal from the differential amplifier **410** and its voltage level can vary from a ground potential to VCC or some designated voltage range. The bias signal **412** is coupled to an oscillator **420** and serves to control the clocking speed or oscillator frequency of the oscillator **420**. For instance, the bias signal **412** can either increase or decrease the frequency of the oscillator **420** based on the voltage level of the bias signal **412**. The comparator **410** uses the bias signal **412** to control the frequency in an analog fashion. Thus the oscillator **420** is

gradually slowed down or sped up over time, rather than being switched on or off instantaneously.

[0036] The frequency blocking signal **414** is a digital output from the differential amplifier **410** and its value varies between a logic high and a logic low. The frequency blocking signal **414** also outputted from comparator **410** is a digital control signal to disable or enable the oscillator **420** and the phase clock generator **430**. Unlike the analog bias signal **412** which needs time to propagate adjustments through the oscillator circuitry, this digital frequency blocking signal **414** can immediately operate the oscillator **420** and clock generator **430**. The frequency blocking signal **414** goes directly to the last stage buffer of the logic blocks and disables the outputs there. The clocking and the pumping action terminates quickly because the last stage buffer is disabled before the effect of the bias signal **412** could work through the clocking logic circuits. For this embodiment, the frequency blocking signal **414** can override the bias signal **412**. The oscillator output **422** is coupled to a phase clock generator **430**. For this embodiment, the clock generator **430** provides four different clock signals CLK1 **432**, CLK2 **434**, CLK3 **436**, CLK4 **438**, with various phases. In other embodiments of charge pumps, the phase clock generator **430** can have more or less number of clock phases and output various other types of clock signals. The phase clock generator **430** drives the pumping action of the pump cells **440** with clock signals **432**, **434**, **436**, **438**.

[0037] The phased clock signals **432**, **434**, **436**, **438**, are coupled to the pump cells **440**. As the clock signals **432**, **434**, **436**, **438**, transition, the pump cells **440** of the charge pump operate to provide a pumped voltage **442**. The pumped output voltage **442** from the pump cells **440** first passes through a large diode device **450**. For this embodiment of

a high precision pump regulation mechanism, the diode **450** is constructed with an S type field effect transistor. Alternatively, an S' device can be used in the diode **450**. S devices are also known as low threshold voltage (V_t) N type field effect transistors. Similarly, S' devices are also low V_t N type field transistors, but S' devices have a threshold voltage lower than that of a S type device. Although S and S' type field effect transistors are described in the present embodiment of the invention, N type and/or N' type transistors may also be used in alternative embodiments.

[0038] Diode **450** here is a very low V_t diode device. The large diode **450** of this embodiment has a size of approximately 2000 square microns, but is not limited as such. This diode can be considered huge relative to typical transistor sized diodes placed in integrated circuits. For alternative embodiments, the diode **450** can have a size anywhere on the order of approximately 2000 square microns or greater. The low V_t and low pass diode device **450** filters out high frequency spikes and ripples in the pump cell output **442**. For this embodiment, the voltage drop across the diode filter **450** due to current loading is absorbed by the charge pump **400** itself and is invisible to external circuits. In addition, each pump cell itself comprises a small diode device internally for the protection of the pump cell from back conductance in certain embodiments. This internal diode is not present in other embodiments. During pumping operation of the pump cells **440**, voltage levels between the pump stages are switched back and forth. At differently levels of the voltage changes, serious back conductance can occur.

[0039] The diode **450** shuts off automatically and stops supplying current from the pump cells **440** if the voltage level at its output starts to move above the level at its input terminal. If the diode **450** did not shut off, the pump cells **440** would continued to supply

current until the feedback reached and notified the comparator **410** to shut down pump operations, which could be too late as the pump output has already overshoot at that point in time. The diode **450** gates current from passing back to the pump cells **440**. Thus the diode **450** can automatically shut down the power supply without waiting for the feedback response. The feedback response will occur, but at a later time. The output of the diode **450** is V_{OUT} **452**, also the charge pump output in this embodiment. V_{OUT} **452** is the pumped supply voltage that can be used on various parts of the chip during algorithms.

[0040] V_{OUT} **452** is also coupled to a resistor divider comprised of resistors R1 **460** and R2 **470**. The resistor divider divides down V_{OUT} **452** for the feedback loop. The pump feedback voltage **462** is taken between R1 **460** and R2 **470** of the resistor divider for comparison against the reference voltage **402** at the comparator **410**. Thus the feedback loop of this embodiment extends from the comparator **410**, through the oscillator **420**, phase clock generator **430**, pump cells **440**, diode **450**, R1 **460**, and back to the comparator **410**. The pump voltage feedback **462** of this embodiment is sampled after the diode filter **450** instead of at the pump cell output **442** in order to reject unwanted pump overshoot and undershoot at the V_{OUT} **452**. The diode **450** also provides some feedback delay in the feedback loop. If the rippling of the pump output node has a high frequency, the lagging of diode can help to remove the rippling effect as V_{OUT} **452** exceeds the pump cell output **442**.

[0041] During operation, the comparator **410** enables the oscillator **420** with a bias signal **412**. The phase clock generator **430** clocks the pump cells **440** of the charge pump based on an oscillator clock signal **422**. The pump cells output a pumped voltage that is

passed through a diode 450 to become a pumped supply voltage V_{OUT} 452. V_{OUT} 452 is sampled for the pump feedback voltage 462 between R1 460 and R2 470. The comparator 410 compares reference voltage 402 and the sampled pump feedback voltage 462 to determine whether V_{OUT} 452, and essentially the charge pump operation, needs to be modified. In response to the comparison, the comparator 410 can alter the charge pump performance. If the comparator 410 determines that the pump feedback voltage 462 is low relative to the reference voltage 402, the pump cells 440 need to be enabled to provide a higher pumped voltage 442. Thus the comparator can increase the bias voltage 412 to the oscillator, which then responds with a higher frequency clock signal 422 to the phase clock generator 430. The higher frequency clock signal to the phase clock generator 430 will cause faster clock signals 432, 434, 436, 438, to increase the pumping operation of the pump cells, eventually increasing the pump output V_{OUT} 452.

[0042] Alternatively, if the comparator 410 determines that the pump feedback voltage 462 is high relative to the reference voltage 402, the pump cells 440 need to be slowed to provide a lower pumped voltage 442. Thus the comparator can decrease the bias voltage 412 to the oscillator, which then responds with a lower frequency clock signal 422 to the phase clock generator 430. The lower frequency clock signal to the phase clock generator 430 will cause slower clock signals 432, 434, 436, 438, to decrease the pumping operation of the pump cells, eventually decreasing the pump output V_{OUT} 452. But if the comparator 410 determines that V_{OUT} 452 is extremely high and needs to be brought down quickly, the comparator can decrease pump output voltage 452 more quickly than biasing the oscillator 420 with a lower bias voltage 412. The pump regulation mechanism of this embodiment can perform frequency blocking and control

on all four phases from the clock drivers of the phase clock generator 430 for rapid pump shutdown to reduce pump overshooting.

[0043] The comparator 410 can use its frequency blocking signal 414 to turn off or disable operation of the oscillator 420 and the phase clock generator 430. The last stage buffers of the clock driver 430 are disabled by the frequency blocking signal to stop outputting phased clock signals. By deactivating the oscillator 420 and the phase clock generator 430, the phased clock signals 432, 434, 436, 438, stop toggling and the pump cells 440 cease pumping operation. The voltage level of V_{OUT} 452 lowers as the charge at V_{OUT} 452 dissipates. When comparator 410 senses from the pump feedback 462 that V_{OUT} 452 has decreased sufficiently, the frequency blocking signal 414 turns back on and enables operation of the oscillator 420 and the phase clock generator 430. The charge pump 400 resumes normal operation and provides a pumped supply voltage again at V_{OUT} 452.

[0044] Thus embodiments of the present invention can provide a solution for high precision wordline control for read and verify operations with MLC flash devices where large voltage variations cannot be tolerated. A charge pump regulation mechanism in accordance with the present invention enables the direct control of the charge pump output through a feedback back loop of the output voltage. For one embodiment of the pump regulation in accordance with the present invention, the total pump output voltage variation can be limited to 100 mV peak to peak or ± 50 mV across varying process corners and conditions. Voltage variations at the pump output 452 are propagated back to the clocking circuits that drive the pump. The pump output in essence helps to signal whether the operation of the pump cells need to be increased, decreased, or even

temporarily ceased. Without the sampling of the pump output voltage and the feeding back of that information to the pump cell control, the charge pump logic would not be able to determine whether the output voltage is at the desired voltage level or within the tolerance range. This more accurate control of the pump output voltage level is needed in the operation of MLC flash devices to ensure proper data. Embodiments of this invention can also assist in the operation of single bit flash devices to better control voltage variations.

[0045] Embodiments of the present invention can provide more precise regulation at minimal costs. The additional circuitry for the comparator **410**, diode **450**, and feedback loop use small amounts of space relative to the total area of the die. And yet, power savings occurs during standby and algorithm execution. The pump regulation mechanism of this embodiment does not impact pump performance in terms of speed or efficiency.

[0046] For an alternative embodiment, the comparator **410** can have multiple frequency blocking signals to separately disable/enable the oscillator **420** and the phase clock generator **430**. Thus the comparator **410** of this alternative embodiment can disable or enable the oscillator **420** or the phase clock generator **430** at different points in time. However, if the oscillator **420** alone is turned off in an attempt to decrease or stop the pumping activity of the pump cells **440**, a lower V_{OUT} **452** can take a longer amount of time in order to be achieved. This is because the phase clock generator **430** does not immediately responded to the shutting off of the oscillator **420** and time is required to propagate the clock signals **422** prior to disabling of the oscillator **420**. On the other hand, disabling the phase clock generator **430** alone without disabling the oscillator can also stop the pumping action at the pump cells **440**. However, because the oscillator **420**

continues to provide a clock signal **422**, the phase clock generator **430** can become confused or restart in an awkward or unknown state later.

[0047] **Figures 5A-D** are flow diagrams illustrating one embodiment of a method for high precision regulation of a charge pump. At block **502** of **Fig. 5A**, a pumped voltage is generated. This pumped voltage is filtered through a low voltage drop diode device at block **504** to become a pumped supply voltage at the output of a charge pump. The pump output voltage is divided at block **506** to obtain a feedback voltage. At block **508**, the divided pump voltage is fed back through a feedback loop to pump control logic, a comparator in this embodiment. A reference voltage is also received at the pump control logic at **510**. This reference voltage serves as a target voltage level at which the charge pump should presently be generating.

[0048] At block **512** of **Fig. 5B**, the reference voltage is compared with the fed back pump voltage at the comparator. The comparator determines whether the voltage levels are equal at block **514**. If the voltages are equal, then the comparator maintains the present clocking frequency of the oscillator to the pump cells. The pump cells continue pumping at block **518**. The pump cells proceed to generate a pumped voltage at block **502** as the cycle repeats.

[0049] But if the voltages are not equal at block **514**, the voltages are also checked whether the reference voltage is greater than the pump feedback voltage at block **520**. If the reference is greater than the feedback voltage, that condition indicates that the charge pump is not pumping enough and providing less than the presently desired voltage. In response, the pump control logic increases the clocking frequency of the oscillator to the pump cells at block **522**. The charge pump cells increase the charge pumping operations

due to the faster clock pulses at **524** to raise the voltage level at the pump output. The pump cells proceed to generate a pumped voltage at block **502** as the cycle repeats.

[0050] Now if the reference voltage is less than the pump feedback voltage at block **520**, that condition indicates that either the charge pump has over pumped and providing more than the presently desired voltage or charge is being fed back to the charge pump output from circuits being supplied by the pump. At block **526** of **Fig. 5C**, the voltages are also checked whether the feedback voltage is much greater than the reference voltage. If the feedback voltage is not much greater than the reference voltage, the issue may be correctable with adjustments to the clocking. The comparator decreases the clocking frequency of the oscillator to the pump cells at block **528**. The charge pump cells decrease pumping operations due to the slower clock pulses at block **530** to lower the voltage level at the pump output. The pump cells proceed to generate a pumped voltage at block **502** as the cycle repeats.

[0051] If the feedback voltage is determined to be much greater than the referenced voltage at block **526**, the clocking to the pump cells is disabled at block **532**. For one embodiment, the disable action entails disabling an oscillator and a phase clock generator. For another embodiment, the disable action involves the disabling of a last stage buffer at the clock output prior to the pump cells. At block **534**, charge pump stops. Because charge pumping has ceased, charge is not being actively supplied from the charge pump. The output voltage from the charge pump should decrease in response as charge is being consumed by circuitry coupled to the pump output. The pump output voltage is divided at block **536** and fed back for sampling at block **538**. The comparator received the pump feedback voltage and also the reference voltage at block **540**.

[0052] At block **542** of **Fig. 5D**, a comparison of the reference voltage and the pump feedback voltage is made. If the reference voltage is greater than or equal to the feedback voltage at block **544**, that indicates that the pump output voltage has decreased sufficiently. Thus the charge pumping can resume. The clocking to the pump cells is enabled at block **546**. For one embodiment, this involves enabling the last stage buffer of the clock generator in order to allow the clock phases to reach the pump cells. For another embodiment, the enabling action entails restarting an oscillator and/or a phase clock generator. The charge pumping resumes at block **548** and the pump cells proceed to generate a pumped voltage at block **502** as the cycle repeats.

[0053] In the foregoing specification, the invention has been described with reference to specific exemplary embodiments thereof. It will, however, be evident that various modifications and changes may be made thereof without departing from the broader spirit and scope of the invention as set forth in the appended claims. The specification and drawings are, accordingly, to be regarded in an illustrative rather than a restrictive sense.